

# Post-Burst Quasi-Periodic Oscillations from GRO J1744–28 and from the Rapid Burster

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## ABSTRACT

The repetitive X-ray bursts from the accretion-powered pulsar GRO J1744–28 show similarities to the type II X-ray bursts from the Rapid Burster. Several authors (notably Lewin et al.) have suggested that the bursts from GRO J1744–28 are type II bursts (which arise from the sudden release of gravitational potential energy). In this paper, we present another similarity between these sources. *Rossi X-ray Timing Explorer* observations of GRO J1744–28 show that at least 10 out of 94 bursts are followed by quasi-periodic oscillations (QPO) with frequencies of  $\sim 0.4$  Hz. The period of the oscillations decreases over their  $\sim 30$ –80 s lifetime, and they occur during a spectrally hard “shoulder” (or “plateau”) which follows the burst. In one case the QPO show a modulation envelope which resembles simple beating between two narrow-band oscillations at  $\sim 0.325$  and  $\sim 0.375$  Hz. Using *EXOSAT* observations, Lubin et al. found QPO with frequencies of 0.039 to 0.056 Hz following 10 out of 95 type II bursts from the Rapid Burster. As in GRO J1744–28 the period of these oscillations decreased over their  $\sim 100$  s lifetime, and they occurred only during spectrally hard “humps” in the persistent emission. Even though the QPO frequencies differ by a factor of  $\sim 10$ , we believe that this is further evidence that a similar accretion disk instability is responsible for the type II bursts from these two sources.

*Subject headings:* X-rays: general, bursts — stars: neutron

## 1. Introduction

GRO J1744–28 is a recently discovered accretion-powered pulsar which shows repetitive X-ray bursts (Kouveliotou et al. 1996; Strickman et al. 1996; Giles et al. 1996; and references therein). Its unusual bursting behavior has been compared (see below) to that of the Rapid Burster (MXB 1730–335), which was discovered 20 years ago by Lewin et al. (1976). Analysis of the X-ray bursts from the Rapid Burster showed that it produced two distinct types of burst: type I, attributed to thermonuclear flashes on the surface of a neutron star; and type II, attributed to the release of gravitational potential energy due to spasmodic accretion. The mechanism responsible for the type II bursts has not been fully understood, although it is almost certainly related to an accretion disk instability (for reviews see Lewin, van Paradijs, & Taam 1993, 1995). Rapidly repetitive type II bursts had previously been observed only from the Rapid Burster, so if the bursts from GRO J1744–28 are also of type II—as convincingly argued by Lewin et al. (1996)—then a comparison of these sources may constrain theories of the burst mechanism.

The pulse period of GRO J1744–28 is 467 ms and the neutron star is in a 11.8 day binary orbit about a low-mass donor star (Finger et al. 1996). During the first 12 hours of bursting observed with BATSE on December 2, 1995, bursts occurred every 3 to 8 minutes, and for one three hour period the burst intervals clustered around  $172 \pm 15$  s (Kouveliotou et al. 1996). Subsequently the burst intervals became longer and more erratic and the burst rate settled at about 30–40 per day (corrected for Earth occultation and live time; Fishman et al. 1996). Burst durations were initially  $\sim 20$ – $30$  s, and settled down to  $\sim 5$ – $10$  s. Unlike the type II bursts from the Rapid Burster, no relationship between the burst fluence and the time to the next (or previous) burst has been reported<sup>1</sup> (Kouveliotou et al. 1996; Strickman et al. 1996).

Using the first observations of GRO J1744–28 with the *Rossi X-ray Timing Explorer* (*RXTE*), Swank (1996) noted that the bursts were followed by a characteristic “dip” in the persistent emission level which took a few minutes to recover. No such dips were seen

<sup>1</sup>A preliminary analysis of the BATSE catalog of over 3000 bursts from GRO J1744–28 shows a statistically significant but weak correlation between the burst fluence scaled to the persistent emission level and the time to the next burst (Kommer et al. 1997).

before the bursts. Subsequent *RXTE* observations showed that the bursts were sometimes preceded by steadily increasing variability in the persistent emission, including “micro” and “mini” bursts (Giles & Strohmayer 1996; Lewin et al. 1996; Giles et al. 1996).

Extensive reviews of the Rapid Burster and its complex behavior can be found in Lewin, van Paradijs, & Taam (1993, 1995); see also references therein. Here we discuss the features of the type II bursts from this source that are relevant to our comparison with GRO J1744–28. The time intervals between type II bursts from the Rapid Burster range from  $\sim 10$  s to  $\sim 1$  hr, with the shorter intervals being more common. Burst durations range from  $\sim 2$  s to  $\sim 680$  s. The burst repetition pattern is that of a relaxation oscillator: the fluence of a type II burst is roughly proportional to the time to the next burst (Lewin et al. 1976; Lewin et al. 1995). Persistent X-ray emission between the type II bursts is observed following long (duration  $> 30$  s) bursts. The persistent flux emerges gradually after high-fluence bursts and decreases prior to the next burst (Marshall et al. 1979; Van Paradijs, Cominsky, & Lewin 1979; Stella et al. 1988a). These pre- and post-burst features are referred to as “dips” in the persistent emission. The spectrum of the persistent emission is relatively soft during the dip just after a burst. It then rapidly increases in hardness, remaining hard for  $\sim 1$ – $2$  minutes before gradually decreasing to again become very soft during the dip preceding the next burst (Stella et al. 1988b). The 1–2 minute period of spectrally hard emission corresponds to a “hump” in the persistent emission light curve.

Lubin et al. (1992) found “naked eye” quasi-periodic oscillations (QPO) following 10 of 95 type II bursts from the Rapid Burster observed with *EXOSAT* in August 1985. The oscillations occurred *only* during the spectrally hard humps (which immediately followed the post-burst dips). The frequency of the oscillations ranged from 0.039 to 0.056 Hz, with a period decrease of 30–50% observed over the  $\sim 100$  s lifetime of the oscillations. The fractional root-mean-square (rms) variation in the oscillations was 5 to 15%. In 8 of the 10 cases, the “naked eye” oscillations were accompanied by  $\sim 4$  Hz QPO with rms variations of 6 to 19% (Lubin et al. 1992).

Several authors have already noted similarities between the bursts from GRO J1744–28 and the Rapid Burster. After the discovery of the bursts from

GRO J1744–28, Kouveliotou et al. (1996) suggested that the release of gravitational potential energy following an accretion instability might be responsible for the bursts. Lewin et al. (1996) made a detailed comparison between the two systems. Noting that both are transient low-mass X-ray binaries in which the accreter is a neutron star, they concluded that the bursts from GRO J1744–28 must be type II based on (i) the hardness of the burst spectra, (ii) the lack of spectral evolution during the bursts, (iii) the fact that the ratio of integrated energy in the persistent emission to that in the bursts was initially too small to allow for a thermonuclear burst mechanism, and (iv) the presence of dips in the persistent emission following bursts (Lewin et al. 1996). Subsequently, Sturmer & Dermer (1996) reached the same conclusion. The possibility of thermonuclear burning in GRO J1744–28 has been discussed by Bildsten & Brown (1997).

In this paper, we present another similarity between the Rapid Burster and GRO J1744–28. Both sources show transient QPO during spectrally hard emission intervals following bursts.

## 2. Observations

Since January 18, 1996, *RXTE* has performed numerous observations of GRO J1744–28. The data discussed here were taken by the PCA instrument and are publicly available. Between January 18 and April 26, 1996, there were 94 main bursts observed (Giles et al. 1996). To refer to these bursts individually, we number them sequentially from 1 to 94.

The light curves of the bursts reveal a rich phenomenology in the burst profiles. Figure 1 (a) shows the “dip” in persistent emission which follows some bursts, as first noted by Swank (1996). A broad “shoulder” (or “plateau”) of emission above the mean pre-burst level immediately follows some bursts, as shown in Figure 1 (b). The shoulder occurs *before* the dip whenever both features are present. Some bursts show large-amplitude oscillations with frequencies  $\sim 0.4$  Hz during their shoulder, as shown in Figure 1 (c) (Kommers et al. 1996).

Oscillations can be seen during the shoulders of the light curves immediately following at least 10 of the 94 bursts. These ten bursts were numbers 8, 12, 14, 18, 43, 53, 65, 68, 77, and 94. Typically 5 to 15 cycles of the QPO are apparent, with as many as  $\sim 25$  cycles seen in the case of burst 65. The low frequency of

the oscillations and the low numbers of cycles make it difficult to use Fourier power spectra to study these QPO. We have instead found the mean periods of the oscillations by estimating the time intervals between successive maxima in the count rates.

The mean frequency of the oscillations over the ensemble of bursts is  $0.38 \pm 0.04$  Hz. The mean frequency of the oscillations after individual bursts varies from  $0.35$  Hz  $\pm 0.02$  Hz in burst 65 to  $0.49 \pm 0.03$  Hz in burst 12. (The uncertainty in these figures represents the uncertainty in the mean frequency.) The period of the QPO following a given burst typically wanders non-monotonically about a mean period by  $\sim 20$  percent over the lifetime of the oscillations. Using the  $\chi^2$  statistic we exclude (at the  $2\sigma$  level or better in each of the 10 bursts) the null hypothesis that the period between successive QPO pulses is constant.

To identify any overall tendency towards increasing or decreasing QPO periods, we looked for bursts where the Spearman rank-order correlation coefficient ( $r_s$ ) indicated that the time intervals between QPO pulses were correlated (or anti-correlated) with arrival time. In no case did we find a positive  $r_s$ , which would have indicated an overall trend towards increasing periods. For bursts 18, 53, 65 (see Figure 2), and 94, we found an anti-correlation at the  $2\sigma$  level or greater. In these bursts the QPO period tends to decrease by 10 to 20 percent over the lifetimes ( $\sim 50$  to 80 s) of the oscillations.

The fractional rms variations of the oscillations range from  $\sim 5$  to 13%. Using the counts to flux conversion  $4.1 \times 10^{-12}$  erg cm $^{-2}$  s $^{-1}$  per count (total PCA band; Giles et al. 1996) the rms variations in flux units range from  $1.2 \times 10^{-9}$  erg cm $^{-2}$  s $^{-1}$  to  $1.4 \times 10^{-8}$  erg cm $^{-2}$  s $^{-1}$ .

The shoulders during which the post-burst oscillations occur are spectrally harder than the persistent emission. Figure 2 (top panel) shows a hardness ratio for burst 65. The hardness is defined as the count rate (averaged over 1.0 s) in the 3–5.6 keV range divided by that in the 2–3 keV range. The middle panel shows the power spectrum as a function of time. Higher power levels are shown with darker shades. The presence of the QPO is shown by a dark band at 0.4 Hz lasting from the end of the burst until  $\sim 100$  s after the peak. The bottom panel shows the burst intensity profile. The spectrum of the burst counts is clearly harder than that of the persistent emission, but even after the main part of the burst subsides the hardness

ratios during the presence of the QPO (20 to 100 s after the burst) exceed those of the pre-burst persistent emission.

The QPO following burst 65 show a modulation envelope reminiscent of “beating” between oscillations at separate frequencies; see the bottom panel of Figure 2. The count rates shown in the inset have been smoothed with a boxcar average to highlight the envelope of the (roughly) 0.05 Hz “beats”. If this modulation envelope can be attributed to simple beating, the two narrow-band oscillations must occur concurrently and have roughly comparable amplitudes. An estimate of the two frequencies involved can be obtained from the mean frequency  $f_{ave} = (f_1 + f_2)/2$  and the beat frequency  $f_{beat} = |f_1 - f_2|$ . The mean frequency for the  $\sim 25$  cycles of QPO following this burst is  $0.35 \pm 0.02$  Hz. The two frequencies which are beating must then be roughly  $f_1 = f_{ave} - f_{beat}/2 = 0.325$  Hz and  $f_2 = f_{ave} + f_{beat}/2 = 0.375$  Hz. The average frequency wanders by about 20%, so if beating is responsible for the apparent modulation envelope then the frequencies of the two narrow-band oscillations wander as well. The presence of a similar phenomenon following other bursts is difficult to determine because fewer cycles are available.

Over the course of the January—May 1996 *RXTE* observations, the burst fluence, peak flux, and persistent emission level each decreased (approximately linearly) by a factor of  $\sim 4\text{--}5$  (Giles et al. 1996). The average frequency and rms amplitude of the post-burst QPO show no significant ( $> 2\sigma$ ) correlations with any of these quantities. QPO with nearly the same frequency are seen in bursts for which the persistent emission level differs by a factor of  $\sim 4$ .

Although our analysis focused on the December 1995–May 1996 outburst of GRO J1744–28, we note that post-burst oscillations were also detected following a burst in June 1996. This burst occurred when the source temporarily resumed bursting activity at a lower level than the main December 1995–May 1996 outburst (Jahoda, Strohmayer, & Corbet 1996). Kommers et al. (1996) reported 0.4 Hz oscillations during a  $\sim 25$  s “shoulder” following the sixth of 7 bursts observed with the PCA on June 4, 1996. The fractional rms amplitude of these oscillations was  $25 \pm 5$  percent. A second large outburst from GRO J1744–28 has been in progress since December 2, 1996, but we have not yet analyzed these observations (Kouveliotou et al. 1997; Stark et al. 1997).

### 3. Discussion

The  $\sim 0.4$  Hz oscillations following some bursts from GRO J1744–28 are reminiscent of oscillations that have been seen following some type II bursts from the Rapid Burster. This likeness between the two sources complements the comparisons made by Lewin et al. (1996). Although it is not certain that the post-burst oscillations are the same phenomenon in both sources, the following similarities are worth consideration. (i) The post-burst oscillations follow bursts that do *not* show the profiles or spectral evolution characteristic of Type I (thermonuclear flash) bursts. (ii) The oscillations occur during a period of spectrally hard emission. (iii) When an overall change in QPO period is observed, it is a decrease: 10–20% for GRO J1744–28, and 30–50% for the Rapid Burster. (iv) The fractional rms amplitude of the oscillations is roughly 5–15%.

There are some differences, however. (i) The frequency of the post-burst oscillations in GRO J1744–28 is roughly 0.4 Hz while in the Rapid Burster, the post-burst oscillations have frequencies of 0.04 Hz and are in some cases accompanied by 4 Hz QPO. (ii) In GRO J1744–28, the oscillations occur *before* the dip in the persistent emission; but in the Rapid Burster, they appear *after* the dip (Lubin et al. 1992).

Cannizzo (1996a, 1996b) has shown that a simple numerical model of a thermal-viscous accretion disk instability can reproduce some features of the GRO J1744–28 bursts. In his model, interplay between radial and vertical energy transport in the disk causes oscillations in the ratio of gas pressure to total pressure (denoted by  $\beta$ ). These oscillations increase in amplitude and eventually become non-linear, leading to a Lightman-Eardley instability (Lightman & Eardley 1974). For specific choices of the inner and outer disk radii ( $r_{inner} = 10^{7.5}$  cm,  $r_{outer} = 10^9$  cm) and the form of the viscous stress, integration of the time-dependent model reproduces the  $\sim 1000$  s recurrence times and the  $\sim 10$  s durations of the bursts as well as the post-burst dips. Cannizzo (1996b) also points out that the increased variability *before* bursts may be related to the oscillations in  $\beta$  that precede the instability. These oscillations may occur in a variety of modes, but in his idealized case appear to have frequencies of about 0.05 Hz (Cannizzo 1996b). It remains to be seen whether this model can explain the oscillations reported here.

Abramowicz, Chen, & Taam (1995) have shown

that low-frequency oscillations in mass flow can arise in accretion disk-corona systems. In their model, the development of a Lightman-Eardley instability is moderated by energy dissipation in the coronal region, which lies above the thin disk. They propose that the strong  $\sim 0.042$  Hz oscillations seen in the Rapid Burster may arise from such a mechanism. The frequency of these QPO may be relatively insensitive to the accretion rate, since it is determined by several competing factors including the radius of the inner accretion disk. The spectrum of the QPO is expected to be hard whenever the QPO originate from the hot inner region (Abramowicz et al. 1995).

The common feature responsible for oscillatory behavior in these models is the presence of a mechanism which couples the vertical energy transport to the radial energy flux. In Cannizzo's model, this mechanism also acts to produce the bursts. To make a quantitative comparison of these models with the characteristics of the post-burst oscillations in GRO J1744–28 and the Rapid Burster, one would have to know what QPO frequencies are expected based on the physical parameters that distinguish the two sources. The magnetic field strength and inner disk radius in particular should be quite different (Lewin et al. 1996; Finger et al. 1996; Sturmer & Dermer 1996), which might account for the factor of  $\sim 10$  difference in post-burst QPO frequency. Detailed information of this kind has not yet been presented for the models of Cannizzo (1996a,b) or Abramowicz et al. (1995).

The presence of transient post-burst QPO is another similarity between the bursts from GRO J1744–28 and the type II bursts from the Rapid Burster. Combined with the comparison of Lewin et al. (1996), this similarity is further evidence that the bursts from GRO J1744–28 are of type II. If the same disk instability is responsible for the type II bursts from each of these sources, then the post-burst oscillations provide another observational benchmark for models of the burst mechanism as well as the QPO.

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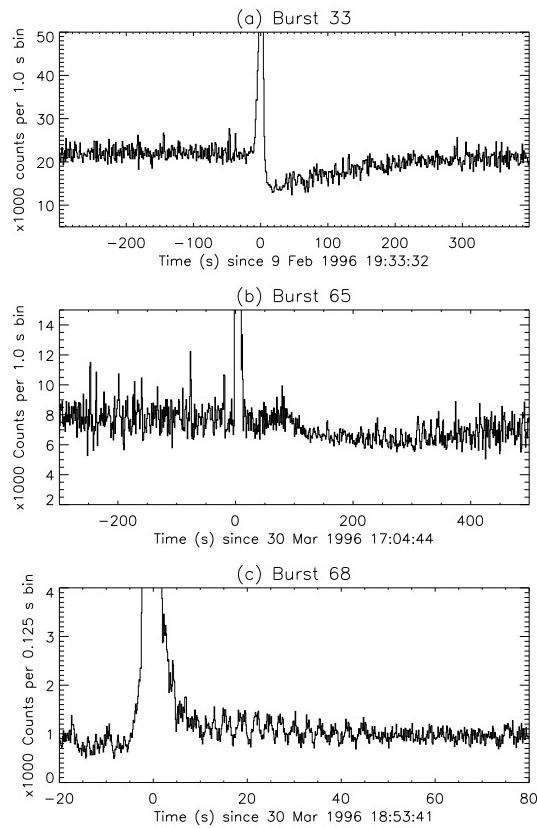


Fig. 1.— Light curves of 3 bursts from GRO J1744–28. The horizontal and vertical scales are each different to highlight the feature of interest. Panel (a) shows the “dip” following burst 33. Panel (b) shows a “shoulder” after burst 65; it occurs before a slight “dip”. QPO with a mean frequency of  $\sim 0.35 \pm 0.02$  Hz are present in the shoulder but are not apparent at this scale and time binning. Panel (c) shows an example of strong QPO with mean frequency  $0.37 \pm 0.03$  Hz occurring during the shoulder after burst 68. The termination of the shoulder and the “dip” occur after the plotted time interval.

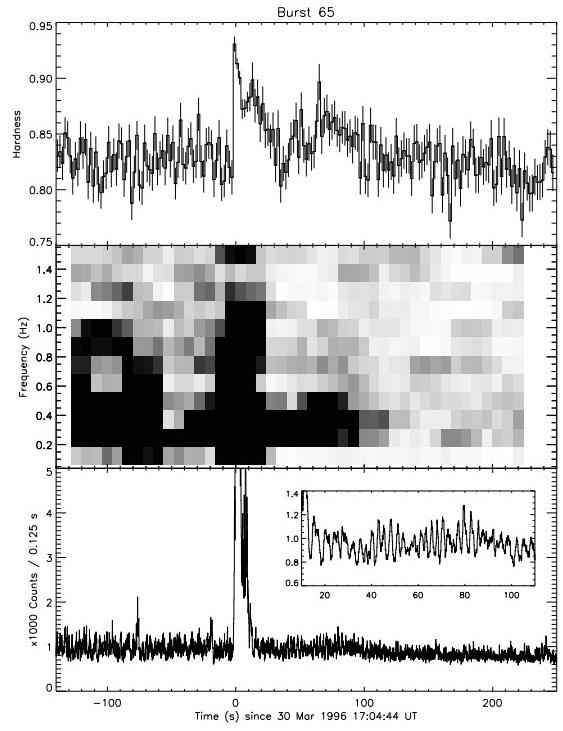


Fig. 2.— Hardness, power spectrum, and intensity profile of burst 65. The top panel shows the ratio of the 3–5.6 keV count rate to the 2–3 keV count rate. (No instrumental dead time corrections have been applied, which may affect the hardness during the burst. The hardness during the shoulder is not significantly affected by dead time.) The middle panel shows a power spectrum with higher powers represented by darker shades. The lower panel shows the intensity profile. Notice that the  $0.35 \pm 0.02$  Hz QPO occur after the burst, and the spectrum during their presence is relatively hard. The inset shows the portion of the intensity profile during which the QPO were observed. The data in the inset have been smoothed with a boxcar average to highlight the apparent beating between oscillations at  $\sim 0.325$  Hz and  $\sim 0.375$  Hz.